Chapter 8

A New Trend in Cryoseismology: A Proxy for Detecting the Polar Surface Environment

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Additional information is available at the end of the chapter

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Abstract

"Cryoseismology" is a new branch of interdisciplinary science, which treats glacier-related seismic events and their dynamics associated with the variable phenomenon of the Earth's surface. Cryoseismology is considered to be one of the proxies for detecting environmental variations, particularly in the polar region, which contains the majority volume of the cryosphere of the planet. Various kinds of cryoseismic signals recently reported are reviewed by classifying them into several categories on the basis of their occurrence locations and focal dynamics. Temporal-spatial variations in cryoseismic activities and their wave propagation characteristics could demonstrate a new image of cryodynamics, which have not yet been known well before but have a significant impact on the global environment and human activities.

Keywords: cryoseismology, polar region, seismic features, surface environment, global warming

1. Introduction

Several kinds of environmental signals associated with the ocean-cryosphere-solid Earth systems have recently been detected in the polar region. Glacier-related seismic signals with a small magnitude are generally called "ice quakes" (or "ice shocks") and can be generated by cryosphere-related dynamics. Such cryoseismic-originating sources can be classified into the movements of ice sheets, ice caps, sea ices, oceanic tidal cracks, and icebergs and the calving fronts of the ice caps, ice streams, and glaciers [1–5]. In this regard, cryoseismic waves are likely to be influenced by temporal-spatial variations in environmental conditions, and continuous research on their variability provides indirect evidence of the climate change. As large glacial earthquakes are the most prominent phenomena found recently in the polar region, particularly around Greenland [6–8], the new innovative studies conducted in seismology are strikingly encouraged by the long-term monitoring observations under extreme conditions in polar regions. Moreover, seismological investigations during the International Polar Year (IPY 2007–2008) were compiled and published including the related topics on cryoseismology [9].

Taking these current topics into account, in this chapter, new trends in "cryoseismology" are reviewed in addition to the previously conducted research studies as shown in Chapter 6. Various kinds of recent cryoseismic studies are demonstrated by classifying them into each section on the basis of their occurrence locations and focal dynamics, that is, ice shelves, outlet glaciers, margins of continental ice sheet, continental cliffs, sea ices, icebergs, oceanic tides, tide cracks around the coast, pressure ridges among bays, the basal sliding of the ice sheet, triggered seismic events associated with out-flood water from subglacial lakes, volcanic activities beneath the ice sheet, and other origins. The most important aspect is covered by the generation mechanism of cryoseismic events associated with global warming/climate change as one of the remarkable natural features in the polar region. Temporal-spatial variations in the glacier-related seismic activities as well as the propagation characteristics of their wavefields will give rise to a new horizon in "cryodynamics," which have not yet been well understood by both scientists and the general public.

2. Outlet glaciers and continental margins of ice sheets

Longitudinal seismic waves were reported in the Ross Ice Shelf (RIS) excited by the Whillans Ice Stream (WIS) stick-slip events [10]. The observations of longitudinal waves from the WIS slip events had been propagating hundreds of kilometers across RIS detected by more than 20 broadband seismographs deployed on the ice. The WIS slip events consisted of a rapid basal slip concentrated at three high-friction regions (often termed sticky spots or asperities) within a period of about 25 minutes. Compression displacement pulses from all three sticky spots were detected across most of the RIS up to about 600 km away from the source. The largest pulse resulted from the third sticky spot that was located along the northwestern grounding line of WIS. Thus, the study of this phenomenon should lead to an advance in understanding how the ice shelf responds to sudden forcing around the periphery, such as triggered ice quakes in the continental ice sheets [11].

Repeating glacial earthquakes revealed a migration process of subglacial sticky spots in the Transantarctic Mountains (TAM) [4]. Winberry et al. leveraged recent advances in seismograph coverage from TAM to study relatively large glacial seismic events (with a magnitude more than 2) that can be observed at regional distances. They reported on five newly discovered and one previously studied sequences of repeating glacial earthquakes. These new seismic sequences revealed that families could remain active for up to the last 7 years. In addition, by tracking subtle changes in relative arrival times as well as waveform similarities, they deduced that these sticky spots originate from migrating bands of basal debris.

Lipovsky and Dunham [12] simulated the tremors of the 200-km scale ice-stream stick slip of WIS. These tremors were considered to be episodes of swarms of small-scale repeating earthquakes. These events are evenly spaced in the timeline, and the spacing interval gives rise to the spectral peaks at integer multiples of the recurrence frequency 10–20 Hz. Numerical simulations of these tremor episodes give rise to information on the evolution of rate- and state-dependent fault friction and wave propagation from the fault patch to a seismograph over the ice area. By comparing synthetic seismograms to the observed ones, a fault patch area of 10 m^2, a bed shear modulus of 20 MPa, an effective pressure of 10 kPa, and a frictional state evolution distance of 1 μm were derived. These slip events are found to occur twice a day, in spite of the skipped events that have been increasing in frequency over the last few years and more.

In the Arctic region in addition to the Antarctic, de Juan et al. [13] studied a sudden increase in tidal response linked to calving and acceleration at a large Greenland outlet glacier. Flows of ice streams have known to be modulated by ocean tidal forcing at the terminus of the glaciers. The decimeter-level periodic positioning variations were found at Helheim Glacier in response to the tidal forcing. Also, the transient increases over 100% responded to the tidal forcing, followed by the occurrence of glacial earthquakes associated with the calving events. The occurrence times and their amplitudes correlate well with the step-like increases in the glacier speed and longitudinal strain rate of the cogenerating glacial earthquakes. The enhanced response to the ocean tides can be explained by a temporary disruption of the subglacial drainage system and a reduction in the friction at the bottom of the ice sheet and the bedrock surface.

Subglacial discharge events have a great effect on the basal movement of the glaciers and erode and redeposit the sediment. At tidewater termini of glaciers, discharge events drive submarine terminus melting, affecting the fjord circulation. Bartholomaus et al. [14] reported observations of hourly to seasonal variations in 1.5–10 Hz seismic tremors at Mendenhall Glacier of Alaska, which strongly correlate with subglacial discharges but not with the basal movement or the discrete icequake events. Vigorous discharge occurred from tidewater glaciers during the summer seasons of the Northern Hemisphere, in spite of fast basal movements that could limit the formation of subglacial conduits. In addition, seismic tremor observations and a melting model of the glaciers could demonstrate that the drainage efficiency of the tidewater glaciers evolves seasonally.

A detailed field study by using seismic-infrasound monitoring of a tidewater calving glacier (Bowdoin of Greenland) was introduced [15]. Bowdoin Glacier in the northwestern Greenland (~120 km from Thule) is a grounded tidewater calving glacier that has been rapidly retreating since 2008. An observational seismic-infrasound network was installed on July 2015 near the 3-km wide calving front of the glacier to enable near-source monitoring of frontal dynamics. Multiple seismic and infrasound events were recorded and linked to the surface crevassing, calving, presumable hydrofracturing, iceberg rotations, teleseismic earthquakes, helicopter-induced tremors, and so on. The most striking feature of the records was the temporal variability of microseismic activities, which were continuously recorded over a period of 2 weeks. Their results showed a double-peak diurnal oscillation in the number of events (up to 600 events per hour). Using high-resolution surface displacement global positioning system (GPS) measurements, they showed that the correlation between the number of events and tides was relayed through strain rate variations.

3. Ice shelves, icebergs, sea ices, and involved tremors

Evaluating cryospheric seismic events with space and time allows us to monitor cryosphere dynamics. The pattern of cryospheric seismic events was observed and classified at Ekström

Ice Shelf, Antarctica [5]. A year of data at the Neumayer seismic network identified the characteristic events occurring close to the grounding line of the Ekström Ice Shelf. The features of the observed seismic signals are consistent with an initial fracturing and associated resonance of a water-filled cavity. The number of detected events strongly correlated with the period of dominant tidal movements. It is assumed that the cracking developing system could be driven by existing glacier stresses through their bending process. The voids can be filled by the seawater, with exciting observing resonance. By assuming this model, seismic events occur almost exclusively during rising tides where cavities could be opened at the bottom of the glacier, that is, at the sea-ice interface.

Long-period teleseismic detectability and its response to cryosphere variation around Syowa Station, Antarctica, were reviewed by Iwata and Kanao [16] and Storchak et al. [17]. The hypocentral distribution and time variations for detected teleseismic events at Syowa Station were searched by using statistical methods over the last four decades (**Figure 1**). The characteristics of the detected events, magnitude dependency, spatial distributions, and seasonal variations were also demonstrated. In addition to a natural increase in the number of teleseismic events, a technical advance in the seismic observing system and the station infrastructure, together with the improvement of seismic phase reading techniques, could efficiently be combined to increase the detection number of the teleseismic events in the last few decades. Variations in detectability for a longer timeline might be associated with the cryosphere dynamics and its evolution, the meteorological environment, and the sea-ice spreading area around the Antarctic continent.

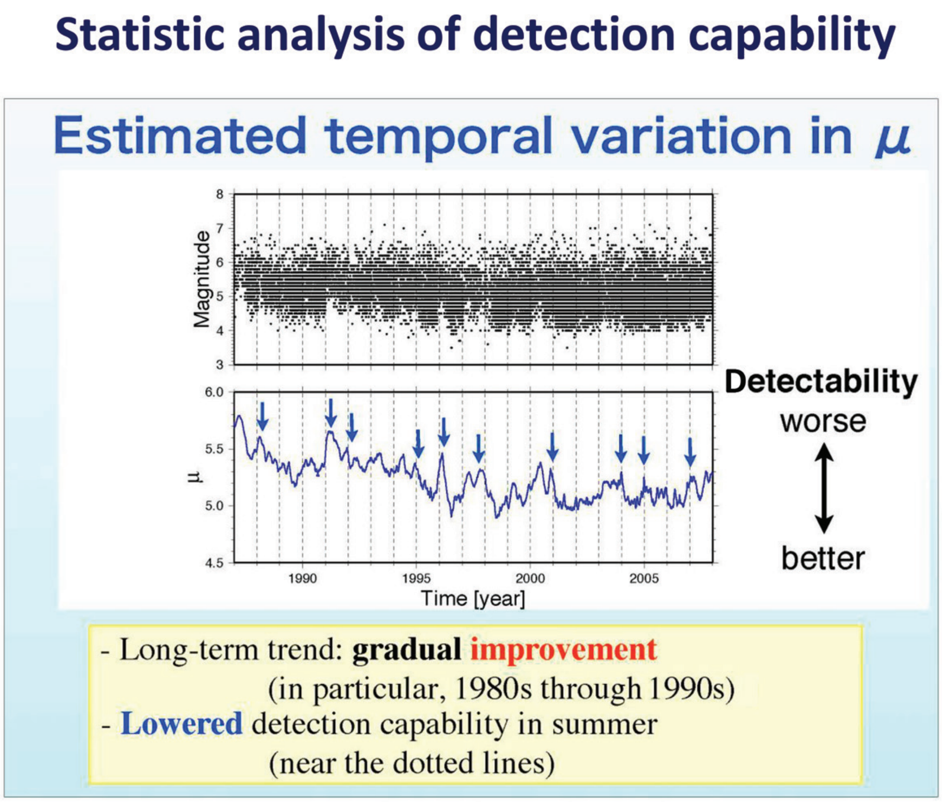

Figure 1. Statistical analysis of the detection capability of teleseismic events at Syowa Station, Antarctica (modified after [16]). (Upper) Magnitude variation during 1987–2008, (lower) estimated temporal variation in the detectability parameter (see [16] in detail). Copyright Clearance Center (CCC, http://www.copyright.com/); license number: 4282221098220, license date: February 4, 2018.

The characteristic seismic tremors with harmonic overtones were clearly observed in Lützow-Holm Bay, East Antarctica during 2014–2015 [18, 19]. More than 120 tremors were recognized by both short-period and broadband seismographs at Syowa Station in the bay from October 2014 to April 2015. Many tremors had characteristics of strong harmonic overtones, in their frequency content of over 1 Hz, representing nonlinear features with duration times from a few minutes to a few hours. The harmonic overtones could be explained by a repetitive source [20], suggesting the existence of several interglacial asperities, which generate the characteristic tremors. It implies that the tremors might be involved in the local origins, presumably the cryosphere dynamics. In this regard, the cryoseismic origins recorded as the tremors were classified into several categories (i.e., collision, calving, crevassing, crashing, etc.): the "crevassing events," which occur in a line along with large cracks inside the fast sea ices in the bay, "discharge events" of the fast sea ices from the bay to the Southern Ocean, "collision events" between the icebergs and the edge of fast sea ices, "crashing movement" of fragmentation between the fast sea ices and the packed sea ices, and other origins related to cryosphere dynamics (**Figure 2**). Similar harmonic tremors, recorded as hydroacoustic signals, associated with drifting icebergs have been identified in the Southern Indian and Pacific Oceans [21].

A more detailed classification of the ice tremors recorded at Syowa Station was conducted [22]. The purposes of the study were to classify the ice-related tremors based on the waveform feature and to reveal the time variation in the occurring numbers. They defined the "ice

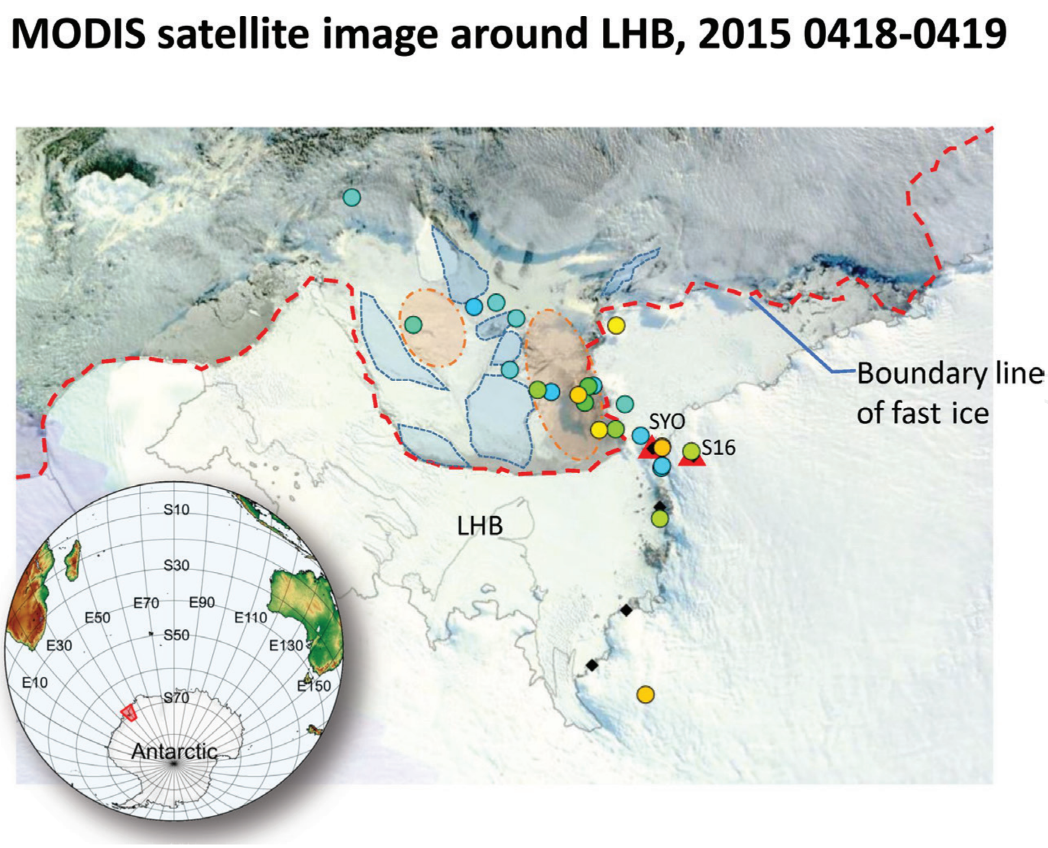

Figure 2. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image around the Lützow-Holm Bay region, East Antarctica on April 18–19, 2015. The hypocenters of infrasound sources involving cryospheric dynamics are shown in colored circles (modified after [19]). Open Access Journal (CC BY 3.0) (first author is M. Kanao).

tremor" as the tremor of which P and S waves were not clear, and the duration was longer than 5 minutes. They found totally 231 ice tremors during the whole year in 2014. The monthly number of ice tremors varied in correlation with the monthly mean temperature except for the months of January to March. Then, they classified these identified ice tremors into four types. Type A had a long duration (10,000 seconds), and the amplitude was small over the waveforms. Type B had irregularly dominant frequency variations over the waveforms. Type C had a continuously decreasing dominant frequency, and the overtone was clearly identified. On April 2006, an iceberg-originated tremor with a similar spectral feature of Type C was recorded at Neumayer Stations, Dronning Maud Land of East Antarctica [23]. Type D had a short duration (about hundreds of seconds) with a gradually increasing/decreasing amplitude, which can be estimated as more local ice-related events.

Characteristics of the seismic waveform recorded by the array deployed at East Ongul Island, where the Syowa Station is located, were reported [24]. In order to detect the source locations of seismic events around the Syowa Station, East Ongul Island of East Antarctica, they carried out a seismic array observation from January 2 to February 2, 2015. They installed seven temporary stations at an outcrop site located 1 km away from the main buildings of the station, consisting of 1-Hz three-component seismometers with an array spacing of 100 m. During this period, two characteristic waveforms were recorded. One event occurred from January 11 at 22:40 Coordinated Universal Time (UTC) to January 12 at 11:20 (UTC), corresponding to sea-ice breaking (laming) events conducted by an icebreaker vessel "Shirase." The peak frequency of the laming events was about 10 Hz. The other event occurred on January 14 at 3:45 (UTC), and its duration was about 13 minutes. Peak frequencies of the tremor were about 2, 4, and 6 Hz, and these peaks varied over time. It is estimated that the tremors arrived from the south to southeast direction with a small slowness by semblance analysis, representing that the sources could be local ones such as the tidal crack generation around the island.

4. Oceanic waves and seismic interferometry

Global trends in extreme microseism intensity were investigated by using the data recorded by the Global Seismographic Network (GSN) and precursor instrumentation to chronicle microseism power extreme events during 1972–2009 [25]. The extreme microseism event number during the winter storm season revealed the widespread influence of the El Nino Southern Oscillation (ENSO). Transoceanic wave propagation that links iceberg calving margins of Antarctica with storms was also investigated, by using deployed seismometers on RIS and on various icebergs adrift in the Ross Sea [26]. It was suggested that if the sea swell influences the iceberg calving and breakup, a teleconnection exists between the Antarctic ice-sheet mass balance and the weather systems worldwide. Broadband seismic stations deployed across RIS studied ocean gravity wave-induced vibrations [27]. Initial data showed both dispersed infra-gravity (IG) waves and ocean swell–generated signals resulting from waves that originate from the North Pacific. The dominant IG band signals exhibit predominantly horizontal propagation from the north.

The array detection of Antarctic microseisms was conducted to evaluate the effect of sea ices and the Southern Ocean storms [28]. The results were obtained from a 60-km aperture array deployed for 2 months on WIS in West Antarctica. Single-frequency (~15 s) Rayleigh wave microseisms

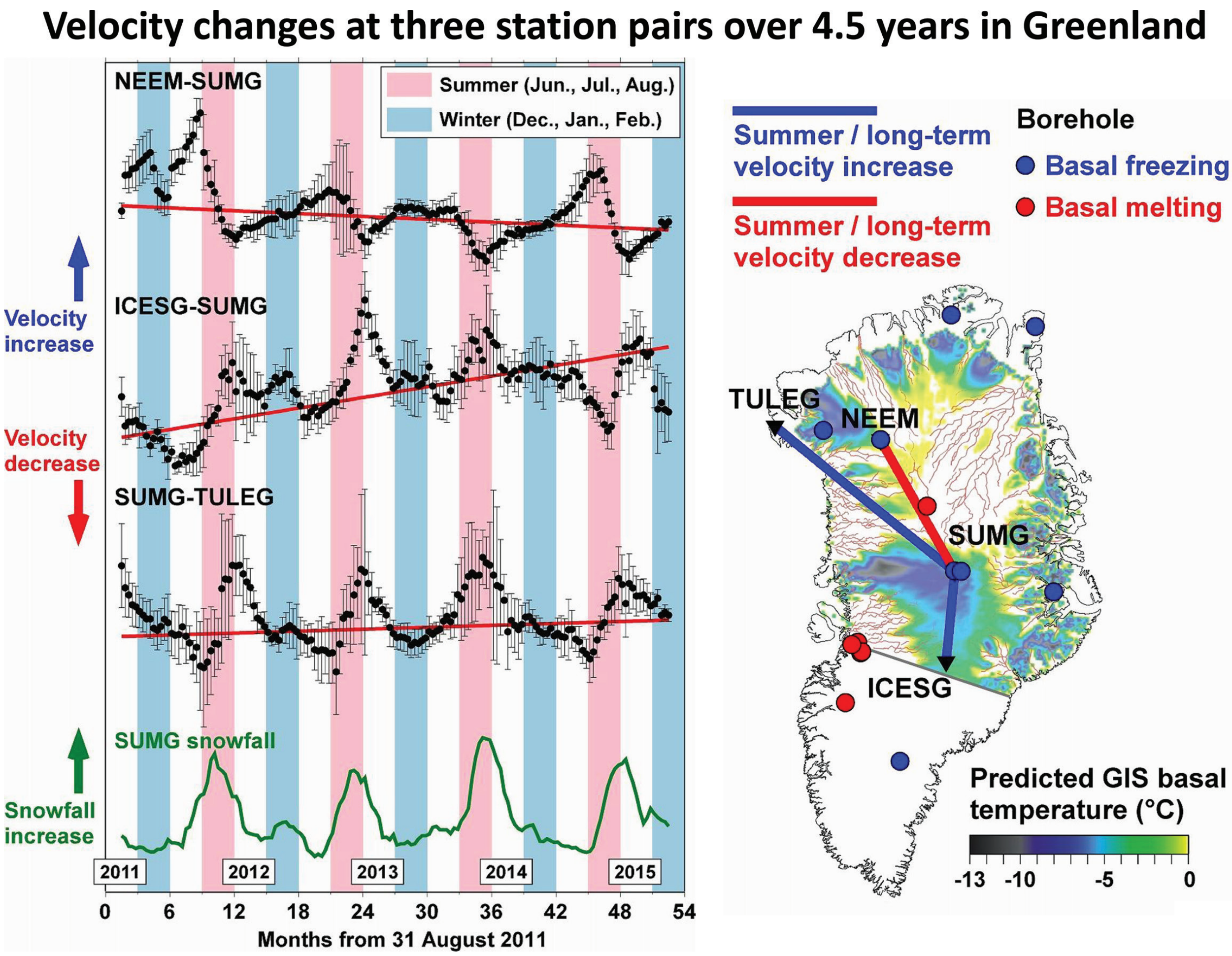

Figure 3. (Left) Seismic surface (Rayleigh) wave phase velocity changes at three station pairs over 4.5 years in Greenland. (Right) Comparison with estimated GrIS basal temperature [34] (modified after [30]). Open Access Journal (CC BY 3.0) (one of the authors is M. Kanao).

were located at the three coastal source areas of strong microseism generation around the continent with their intensity heavily modulated by the local sea-ice extent. Long-period double-frequency (9–11 s) Rayleigh wave microseisms were generated in the deep ocean and correlated with the ocean wave modeling. In contrast, short-period double-frequency microseisms (5–7 s) were found to contain both coastal-sourced microseisms and deep ocean-sourced body wave microseisms. The strongest arrival in this band was often observed to propagate faster than the predicted fundamental mode Rayleigh wave and slower than the potential body waves and was interpreted to be an Lg phase propagating through the Antarctic continental crust.

The basal conditions of the Greenland Ice Sheet (GrIS) are a key research topic in climate change studies. The meltwater is found to influence the occurrence of deep stick-slip ice quakes near the base of GrIS [29] by using a 17-seismometer array temporarily deployed on the western margin of GrIS. The recent developing seismic network has also provided a new opportunity for direct, real-time, and continuous monitoring of GrIS. A seismic interferometry study by using the broadband continuous waveform data from GrIS was carried out [30]. The GreenLand Ice Sheet monitoring Network (GLISN) is an international project by 14 countries to monitor dynamic changes in GrIS, by deploying 32 broadband seismic stations in and around Greenland [8, 31]. Daily cross-correlation functions (CCFs) for all possible pairs of the GLISN stations were computed. As a result, they found a nearly constant Rayleigh wave group velocity of 2.8 km/s, for a range of 2–14 s, on CCF of the NEEM and Schumit-G (NEEM-SUMG) station pair. The ambient noise source was well corresponded to a known source of microseisms at the southern tip of Greenland.

The ambient noise surface wave data were utilized from seismic stations all over Greenland for a 4.5-year period to detect changes in Rayleigh wave phase velocity between the seismic station pairs [30] (**Figure 3**). They observed clear seasonal and long-term velocity changes for many pairs and proposed a plausible mechanism for these changes. Dominant factors driving the velocity changes might be seasonal and due to long-term pressurization/depressurization of GrIS and shallow bedrock by air and ice mass loading/unloading. However, the heterogeneity of the GrIS basal conditions might impose a strong regionality on the results. An interesting feature is that even at adjacent two station pairs in the inland GrIS, one pair shows a decrease in velocity, while another shows an increase in velocity as a response to the high air and snow pressure. The former pair might be located on a thawed bed that decreases the velocity by increasing meltwater due to pressure melting, whereas the latter pair might be located on a frozen bed that increases the velocity by compacting the ice and shallow bedrock. The results suggest that surface waves are very sensitive to the GrIS basal conditions, and further observations will contribute to get a more direct and quantitative estimation of water balance in the Arctic region.

5. Inland ice sheets and dynamics of basal environments

The detection of seismic sources associated with the ice movement in Antarctica using a regional array deployment by combining the global network data has been conducted in the last few years. A previously unreported type of seismic source in the firn layer of the East Antarctic ice sheet was investigated in detail by using the data from the Polar Earth Observing Network (POLENET) project deployed during the IPY [32]. The newly detected local events occurring inside the ice-sheet layer could presumably be cryodynamic in origin. These sources, named “firn quakes,” are characterized by dispersed surface wave trains with frequencies of 1–10 Hz, propagating distances up to 1000 km. Lough et al. [32] proposed that these events are linked to the formation of small crevasses in the firn layers at the surface of the ice sheet, and several seismic events could correlate with shallow crevasse fields mapped in the satellite imagery. The hypocentral location of these events appeared to be close to the location of the existing crevasses, that is, nearby the upstream of Lambert Glacier and the inland area of TAM. Related topics involving seismic detection in the inland plateau of the ice sheet are also introduced in Chapter 7.

Subglacial volcanoes with high-heat flow are found to exist in Marie Byrd Land, a highland region of West Antarctica. Lough et al. [33] used the POLENET data to show the evidence of the existence of two seismic swarm activities occurring in the depth range of 25–40 km beneath the subglacial topographic and magnetic high areas, located at 55 km southward from the youngest subaerial volcano of Marie Byrd Land. They interpreted the swarm events as the deep long-period earthquakes based on their unusual frequency contents. Such earthquakes occurring beneath the active volcanoes are considered to be caused by the deep magmatic activity and, in some cases, precede eruptions.

Seismic waves from distant, large earthquakes can almost instantaneously trigger shallow micro-earthquakes and deep tectonic tremors as they pass through the Earth's crust. The triggered seismicity is generally considered to reflect a shear failure on critically stressed fault planes and is thought to be driven by dynamic stress perturbations from both the Love and the Rayleigh types of surface seismic waves. Peng et al. [11] investigated the POLENET seismic data from the Antarctic for the 2010 M 8.8 Maule earthquake in Chile. They identified a lot of high-frequency signals during the passage time windows of the Rayleigh waves caused by the Maule earthquake. The interpretation of these characteristic signals is the triggered ice quakes within the Antarctic ice sheet by the Rayleigh waves. The source locations of these triggered ice events are difficult to determine by only global seismic networks; however, the triggered events generated surface waves. Therefore, they are probably formed by the near-surface layers of the ice sheet and caused by the tensile fracturing of the near-surface ice layer or the brittle fracture events by the changes in the volumetric strain.

6. Summary

A new trend of "cryoseismology," introduced in this chapter, covered the recent achievements involving the glacier-related seismic events and the associated phenomenon of the Earth's surface observed in the bipolar region (Antarctica and Greenland). Several fruitful scientific achievements were introduced regarding the seismic excitation by the stick-slip events in the West Antarctic ice stream, array detection of microseisms in the Antarctic and their relationship with the sea ices and Southern Ocean storms, seismic events of a tidewater calving glacier in Greenland, seismic interferometry over the whole Greenland, array analysis of infrasound and harmonic tremors in Lützow-Holm Bay of East Antarctica, and others. Various kinds of cryoseismic signals recently reported are reviewed by classifying them on the basis of their occurrence locations and focal dynamics. Time-space variations in the activities and propagation characteristics should produce a new horizon for understanding the cryosphere dynamics, which have not been well known before but could presumably have a great impact on conducting human activities in the twenty-first century.

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References

[1] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic and hydroacoustic tremor generated by colliding icebergs. Journal of Geophysical Research. 2008;**113**:F03011. DOI: 10.1029/2008JF001005

[2] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic observations of glaciogenic ocean waves on icebergs and ice shelves. Journal of Glaciology. 2009;**55**:193-206

[3] Zoet LK, Anandakrishnan S, Alley RB, Nyblade AA, Wiens DA. Motion of an Antarctic glacier by repeating tidally modulated earthquakes. Nature Geoscience. 2012;**5**:623-626

[4] Winberry JP, Anandakrishnan S, Wiens DA, Alley RB. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans ice stream, Antarctica. Geophysical Research Letters. 2013;**40**:312-315

[5] Hammer C, Ohrnberger M, Schlindwein V. Pattern of cryospheric seismic events observed at Ekström ice shelf, Antarctica. Geophysical Research Letters. 2015;**42**:3936-3943

[6] Ekström G, Nettles M, Tsai VC. Seasonality and increasing frequency of Greenland glacial earthquakes. Science. 2006;**311**:1756-1758

[7] Nettles M, Ekström G. Glacial earthquakes in Greenland and Antarctica. Annual Review of Earth and Planetary Sciences. 2010;**38**:467-491

[8] Clinton JF, Nettles M, Walter F, Anderson K, Dahl-Jensen T, Giardini D, Govoni A, Hanka W, Lasocki S, Lee WS, McCormack D, Mykkelveit S, Stutzmann E, Tsuboi S. Real-time geophysical data enhance earth system monitoring in Greenland, Eos trans. AGU. 2014;**95**:13-24

[9] Kanao M, Zhao D, Wiens DA, Stutzmann E. Recent advance in polar seismology: Global impact of the international polar year—Overview. Polar Science. 2015;**9**:1-4. DOI: 10.1016/j.polar.2014.12.003

[10] Pratt MJ, Winberry JP, Wiens DA, Anandakrishnan S, Alley RB. Seismic and geodetic evidence for grounding-line control of Whillans ice stream stick-slip events. Journal of Geophysical Research - Earth Surface. 2014;**119**:333-348. DOI: 10.1002/ 2013JF002842

[11] Peng Z, Walter JI, Aster RC, Nyblade A, Wiens DA, Anandakrishnan S. Antarctic icequakes triggered by the 2010 Maule earthquake in Chile. Nature Geoscience. 2014;**7**:677-681

[12] Lipovsky BP, Dunham EM. Tremor during ice-stream stick slip. The Cryosphere. 2016;**10**: 385-399. DOI: 10.5194/tc-10-385-2016

[13] de Juan J, Elósegui P, Nettles M, Larsen TB, Davis JL, Hamilton GS, Stearns LA, Andersen ML, Ekström G, Ahlstrøm AP, Stenseng L, Khan SA, Forsberg R. Sudden increase in tidal response linked to calving and acceleration at a large Greenland outlet glacier. Geophysical Research Letters. 2010;**37**:L12501. DOI: 10.1029/2010GL043289

[14] Bartholomaus TC, Amundson JM, Walter JI, O'Neel S, West ME, Larsen CF. Subglacial discharge at tidewater glaciers revealed by seismic tremor. Geophysical Research Letters. 2015;**42**:6391-6398. DOI: 10.1002/2015GL064590

[15] Podolskiy EA, Sugiyama S, Funk M, Walter F, Genco R, Tsutaki S, Minow AM, Ripepe M. Tide-modulated ice flow variations drive seismicity near the calving front of Bowdoin glacier, Greenland. Geophysical Research Letters. 2016;**43**. DOI: 10.1002/2016GL067743

[16] Iwata T, Kanao M. The quantitative evaluation of the annual variation in the Teleseismic detection capability at Syowa station, Antarctica. Polar Science. 2015;**9**:26-34. DOI: 10.1016/j.polar.2014.10.002

[17] Storchak DA, Kanao M, Delahaye E, Harris J. Long-term accumulation and improvements in seismic event data for the polar regions by the international seismological Centre. Polar Science. 2015;**9**:5-16. DOI: 10.1016/j.polar.2014.08.002

[18] Kanao M. Characteristics of seismic wave propagation of harmonic tremors observed at the margin in the Lützow-Holm Bay, East Antarctica. In: Earthquakes—Tectonics, Hazard and Risk Mitigation, Chapter 4. Rijeka, Croatia: InTech. Publisher; 2017. pp. 71-85. DOI: 10.5772/66090. ISBN 978-953-51-2886-1

[19] Kanao M, Murayama T, Yamamoto M-Y, Ishihara Y. Seismic tremors and their relation to cryosphere dynamics in April 2015 around the Lützow-Holm Bay, East Antarctica. International Journal of Geosciences. 2017;**8**:1025-1047. DOI: 10.4236/ijg.2017.88058

[20] Powell TW, Neuberg J. Time dependent features in tremor spectra. Journal of Volcanology and Geothermal Research. 2003;**128**:177-185

[21] Talandier J, Hyvernaud O, Reymond D, Okal EA. Hydroacoustic signals generated by parked and drifted icebergs in the southern Indian and Pacific oceans. Geophysical Jour nal International. 2006;**165**:817-834

[22] Tanaka Y, Hiramatsu Y, Ishihara Y, Kanao M. Classification of ice tremor recorded at Syowa Station in Antarctica. In: Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior, J01-P-01; July 30-August 4, 2017; Kobe, Japan. 2007

[23] Eckstaller A, Müller C, Ceranna L, Hartmann G. The geophysics observatory at Neumayer stations (GvN and NM-II) Antarctica. Polarforshung. 2007;**76**:3-24

[24] Nakamoto M, Miyamachi H, Matsushima T, Kanao M, Yamamoto M-Y. Characteristics of seismic waveform recorded by seismic array at East Ongul Island, Antarctica, JpGU 2016, MTT05-P03, May 22-26; Makuhari, Chiba, Japan. 2016

[25] Aster RC, McNamara DE, Bromirski PD. Global trends in extremal microseism intensity. Geophysical Research Letters. 2010;**37**:L14303. DOI: 10.1029/2010GL043472

[26] MacAyeal DR, Okal EA, Aster RC, Bassis JN, Brunt KM, Cathles LM, Drucker R, Fricker HA, Kim Y-J, Martin S, Okal MH, Sergienko OV, Sponsler MP, Thom JE. Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in tropics and northern hemisphere. Geophysical Research Letters. 2006;**33**:L17502. DOI: 10.1029/2006GL027235

[27] Bromirski PD, Diez A, Gerstoft P, Stephen RA, Bolmer T, Wiens DA, Aster RC, Nyblade A. Ross ice shelf vibrations. Geophysical Research Letters. 2015;**42**. DOI: 10.1002/2015 GL065284

[28] Pratt JM, Wiens DA, Winberry JP, Anandakrishnan S, Euler GG. Implications of sea ice on Southern Ocean microseisms detected by a seismic array in West Antarctica. Geophysical Journal International. 2017;**209**:492-507. DOI: 10.1093/gji/ggx007

[29] Roeoesli C, Helmstetter A, Walter F, Kissling E. Meltwatrer influences on deep stick-slip icequakes near the base of the Greenland ice sheet. Journal of Geophysical Research - Earth Surface. 2016;**121**:223-240. DOI: 10.1002/2015JF003601

[30] Toyokuni G, Takenaka H, Takagi R, Kanao M, Tsuboi S, Tono Y, Childs D, Zhao D. Changes in Greenland ice bed conditions inferred from seismology. Physics of the Earth and Plan etary Interiors. 2017;**277**:81-98. DOI: 10.1016/j.pepi.2017.10.010

[31] Toyokuni G, Kanao M, Tono Y, Himeno T, Tsuboi S, Childs D, Anderson K, Takenaka H. Japanese contribution to the Greenland ice sheet monitoring network (GLISN). Antarctic Record (New Zealand). 2014;**58**:1-18

[32] Lough AC, Wiens DA, Nyblade AA, Anandakrishnan S. A previously unreported type of seismic source in the firn layer of the East Antarctic ice sheet. Journal of Geophysical Research - Earth Surface. 2017;**120**:2237-2252

[33] Lough AC, Wiens DA, Barcheck CG, Anandakrishnan S, Aster RC, Blankenship DD, Huerta AD, Nyblade AA, Young DA, Wilson TJ. Seismic detection of an active subglacial magmatic complex in Marie Byrd land, Antarctica. Nature Geoscience. 2013;**6**:1031-1035. DOI: 10.1038/ ngeo1992

[34] Rogozhina I, Petrunin AG, Vaughan APM, Steinberger B, Johnson JV, Kaban MK, Calov R, Rickers F, Thomas M, Koulakov I. Melting at the base of the Greenland ice sheet explained by Iceland hotspot history. Nature Geoscience. 2016;**9**:366-369. DOI: 10.1038/ngeo2689

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